New physics from atmosphere: light sgoldstino case

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New Physics in form of light particles

- New light (GeV-scale) very weakly interacting particles are predicted in many BSM scenarios: dark matter, new gauge bosons, dark photon, sterile neutrinos, ALP, supersymmetric models
- Big experimental program at LHC (FASER, SHiP etc.)
- New light particles – feeble interaction with SM, i.e. small production and decay probabilities
- They may be long-lived!
- Production in decays of mesons: at colliders as well as in atmosphere!
- Neutrino experiments are looking for atmospheric neutrinos produced in meson decays: why not look for new particles?

Supersymmetric models

- SUSY - attractive extension of SM, extensively studied at the LHC experiments
- SUSY breaking: hidden sector $\rightarrow$ visible sector
  No direct interactions between visible and hidden sectors
- Transmission of SUSY breaking at a scale M: messengers (gravity, gauge interactions, etc.)
- Spontaneous SUSY breaking: goldstino and its superpartners

(Chiral) Goldstino supermultiplet

- $\Phi = \phi + \sqrt{2}\theta\psi + F_\phi\theta^2$, F_ϕ – auxiliary field
- SUSY — broken $\to F \equiv \langle F_\phi \rangle \neq 0$
- $\sqrt{F}$ — supersymmetry breaking scale
- $\sqrt{F} \gg M_{EW}$ — goldstino supermultiplet decouples – usual MSSM
- $\sqrt{F} \gtrsim M_{EW}$ — we should include S, P and ψ in low energy theory — low scale supersymmetry breaking
- ψ – Goldstone fermion,
- goldstino $\to$ longitudinal gravitino component : $m_{3/2} = \sqrt{8\pi/3}F/M_{Pl}$
- for $\sqrt{F} = 100$ TeV, $m_{3/2} \approx 2.4$ eV – superlight gravitino
- $\phi = (S + iP)/2$, where $S(P)$ — scalar(pseudoscalar) sgoldstino

Interactions of goldstino supermultiplet with SM

- MSSM + goldstino supermultiplet
  $\Phi = \phi + \sqrt{2}\theta\psi + F_\phi\theta^2, \ \langle F_\phi \rangle = F,$

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_{\Phi-K\ddot{a}hler} + \mathcal{L}_{\Phi-gauge} + \mathcal{L}_{\Phi-superpotential}$$

$$\mathcal{L}_{\Phi-K\ddot{a}hler} = -\int d^2\theta\, d^2\bar{\theta}\, \Phi^\dagger\Phi \cdot \sum_k \frac{m_k^2}{F^2} \Phi_k^\dagger e^{g_1 V_1 + g_2 V_2 + g_3 V_3} \Phi_k$$

$$\mathcal{L}_{\Phi-gauge} = \frac{1}{2}\int d^2\theta\, \Phi \cdot \sum_\alpha \frac{M_\alpha}{F} TrW^\alpha W^\alpha + h.c.\,,$$

$$\mathcal{L}_{\Phi-superpotential} = \int d^2\theta\, \Phi \cdot \epsilon_{ij} \left(-\frac{B}{F} H_D^i H_U^j + \frac{A_{ab}^D}{F} Q_a^j D_b^c H_D^i + \ldots \right) + h$$

- Nonrenormalizable, low energy effective theory $E \lesssim \sqrt{F}$
- Weak coupling regime: hierarchy $m_{soft} \lesssim \sqrt{F}$
- Higher order interactions are suppressed by higher powers of F

Interactions of goldstino supermultiplet with SM

Sgoldstino interaction lagrangian with gauge fields and fermions

$$\mathcal{L}_\phi = -\sum_\alpha \frac{M_\alpha}{4\sqrt{2}F} S F^\alpha_{a\,\mu\nu} F^{\alpha\,\mu\nu}_a - \epsilon_{ij}\left(\frac{A^D_{ab}}{\sqrt{2}F}\bar{q}^j_a d^c_b \cdot h^i_D S + \dots\right)$$

$$-\sum_\alpha \frac{M_\alpha}{8\sqrt{2}F} P F^\alpha_{a\,\mu\nu}\epsilon^{\mu\nu\lambda\rho}F^\alpha_{a\lambda\rho} - \epsilon_{ij}\left(i\frac{A^D_{ab}}{\sqrt{2}F}\bar{q}^j_a \gamma^5 d^c_b \cdot h^i_D P + \dots\right)$$

Scalar sgoldstino can mix with the Higgs boson with mixing angle

$$\theta_{Sh} \approx -\frac{4\mu^3 v \sin 2\beta + v^3(g_1^2 M_1 + g_2^2 M_2)\cos 2\beta}{2Fm_h^2}$$

Light sgoldstino phenomenology: decays

see, e.g., Gorbunov, '2000

Main decay channels for sgoldstinos $m_{S,P} < 0.5$ GeV:

$X = S$ or P

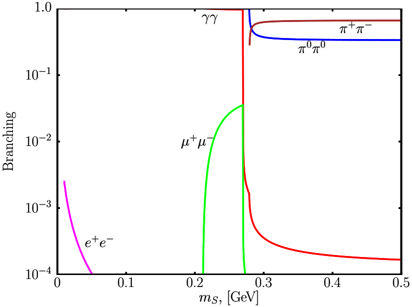
$X \to \gamma\gamma$: $\Gamma \sim \frac{M_{\gamma\gamma}{}^2 m_X^3}{F^2}$

$X \to f_{SM}\bar{f}_{SM}$: $\Gamma \sim \frac{A_f{}^2 m_f^2 m_X}{F^2}$

$S \to \pi\pi$: $\Gamma \sim \frac{M_3{}^2 m_S f(A/M_3)}{F^2}$

$P \to \pi\pi$ is forbidden

$M_{\gamma\gamma} = 2$ TeV, $M_3 = 4$ TeV, $A = 2$ TeV



Decay $P \to \gamma\gamma$ is dominant at least up to $3m_\pi$

Light sgoldstino production in light meson decays

- Scalar sgoldstino S

$$\mathrm{Br}(K^\pm \to \pi^\pm S) \approx 1.3\cdot 10^{-3} \times \left(\frac{Av}{F} + \theta_{Sh}\right)^2 \times \lambda^{1/2}\left(\frac{m_S}{m_K}, \frac{m_\pi}{m_K}\right)$$
$$\mathrm{Br}\left(K_L \to \pi^0 S\right) \approx 5.5\cdot 10^{-3} \times \left(\frac{Av}{F} + \theta_{Sh}\right)^2 \times \lambda^{1/2}\left(\frac{m_S}{m_K}, \frac{m_\pi}{m_K}\right)$$

- Pseudoscalar sgoldstino P

$$P - \pi^0 \text{ mixing: } \sin^2\theta \times \sim \frac{M_3^2 f_\pi^2 m_\pi^4 f(A/M_3)}{F^2 (m_P^2 - m_{\pi^0}^2)^2}$$
$$\Gamma\left(K^\pm \to P\,\pi^\pm\right) \approx \sin^2\theta\,\Gamma\left(K^\pm \to \pi^0\,\pi^\pm\right)\Big|_{m_\pi \to m_P}$$
$$\Gamma\left(\pi^\pm \to P\,e^\pm \nu_e\right) \approx \sin^2\theta \times \Gamma\left(\pi^\pm \to P\,e^\pm \nu_e\right)\Big|_{m_\pi \to m_P}$$
$$\Gamma\left(K^\pm \to P\,e^\pm \nu_e\right) = \sin^2\theta \times \Gamma\left(K^\pm \to P\,e^\pm \nu_e\right)\Big|_{m_\pi \to m_P}$$

NB: Above decays can go through flavor violating couplings

Production of light particles in meson decays in atmosphere

see, e.g. Argüelles, Coloma, Hernandez, Muñoz, '20

Production of S: $M \to S + ...$ $S \to \gamma\gamma$

Production rate:
$$\frac{d\Phi_S}{dE_S d\Omega dX} = \sum_M \int dE_M \frac{1}{\rho\lambda_M} \frac{d\Phi_M}{dE_M d\Omega} \frac{dN_S}{dE_S}$$

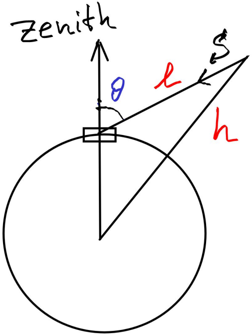
$X = \int dl\, \rho(h)$ – slant depth

$h = \sqrt{R^2 + 2lR\cos\theta + l^2} - R$

$\rho(X)$ – density of atmosphere

$\lambda_M(E_M)$ – decay length of M

$\frac{dN_S}{dE_S}(E_P, E_S)$ – spectrum of S in the decay of meson M



Meson spectra in atmosphere

Fedynitch et al.'12, '15, https://mceq.readthedocs.io

We use MCEq program – Matrix Cascade Equations

$$\frac{d\Phi_M}{dX} = -\frac{\Phi_M}{\lambda_{int,M}} - \frac{\Phi_M}{\lambda_{dec,M}} + \sum_{M'} \int dE_{M'} \frac{\Phi_{M'}}{\lambda_{int,M'}} \frac{dN_M^{int}}{dE_M} + \sum_{M'} \int dE_{M'} \frac{\Phi_{M'}}{\lambda_{dec,M'}} \frac{dN_M^{dec}}{dE_M}$$

$\lambda_{int,M}$ and $\lambda_{dec,M}$ – interaction and decay length of P

$\frac{dN_M^{int}}{dE_M}$ and $\frac{dN_M^{dec}}{dE_M}$ – production spectra of M

Atmospheric model – NRLMSISE-00

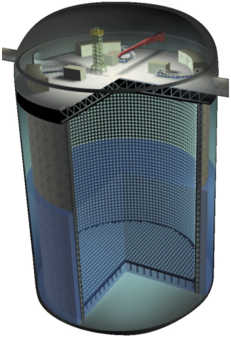
Hadronic interactions: SYBILL-2.3c, QGSJET-II-04, DPMJET-III

Flux of S at the detector:

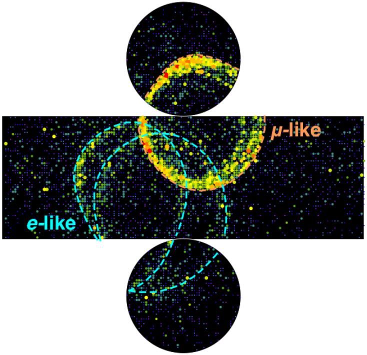
$$\frac{d\Phi_S}{dE_S d\cos\theta} = 2\pi \int dX \; \mathrm{e}^{-l/\lambda_{dec,S}} \left(\frac{d\Phi_S}{dE_S d\Omega dX}\right)_0$$

Signal in Super-Kamiokande

SK view (from Kajita et al. NPB 908 (2016) 14)



Example of event (from arXiv:2311.05105)



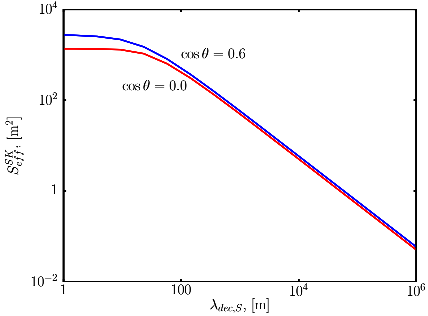
Electron and photons ⟶ e/m showers ⟶ blurred rings

Muons and charged pions ⟶ rings with sharp edges

Signal in Super-Kamiokande

Effective area:

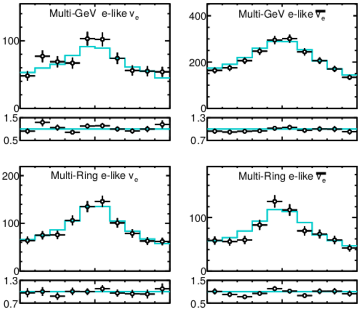
$$S_{eff}^{SK}(\theta, E) = \int dS_\perp \left(1 - e^{-\frac{\Delta_{det}}{\lambda_{dec,S}}}\right)$$



10 bins in $\cos\theta$ [-1,1]
1.3 GeV$\lesssim E_S \lesssim$ 90 GeV

Very conservative estimate: background – atmospheric neutrinos

Atmospheric neutrino oscillation analysis at SK (PRD 97, 072001) - 5326 days, take all multi-GeV e-like events



Procedure

- Fix m_S (or m_P) and dominant production channel in a decay
- Two parameters: τ_S and $Br(M \to S + ...)$
- Expected signal:

$$S_i = \epsilon T \int d\cos\theta \, dE_S \, S_{\mathrm{eff}}^{SK}(\theta, E_S) \, \frac{d\Phi_S}{dE_S \, d\cos\theta}$$

- Find 90% CL bounds using

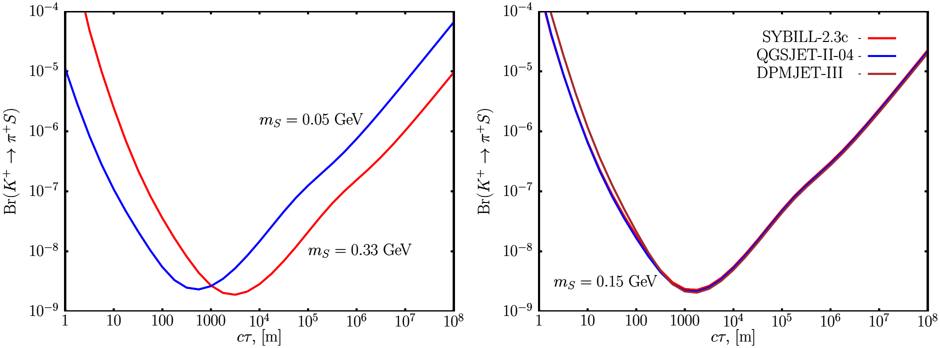
$$\chi^2 = 2 \sum_i \left(S_i + B_i - N_i \left(1 - \log \frac{N_i}{S_i + B_i} \right) \right)$$

- Sensitivity of Hyper-Kamiokande (10 years): larger size and fiducial volume (a factor about 8.4)

$K \to S\pi, S \to \gamma\gamma$: bounds from SK data

Scalar sgoldstino S

Dominant production channels: $K^{\pm} \to \pi^{\pm} S$ and $K_L \to \pi^0 S$

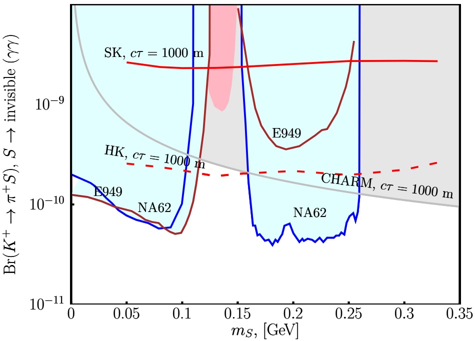


Peak sensitivity – $c\tau_S \sim 10^2 - 10^4$ m

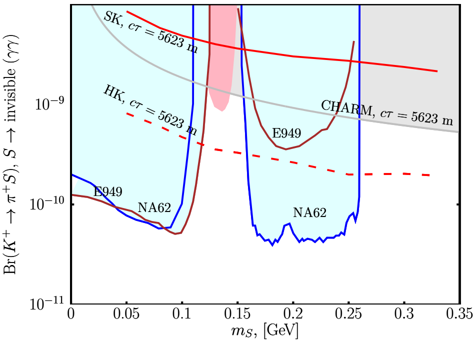
$K \to S\pi, S \to \gamma\gamma$ (long-lived)

Comparison with other experiments

$c\tau = 1000$ m



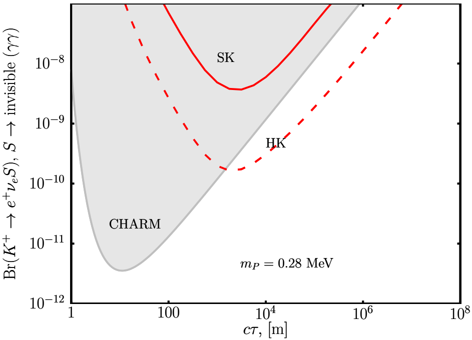
$c\tau = 5623$ m



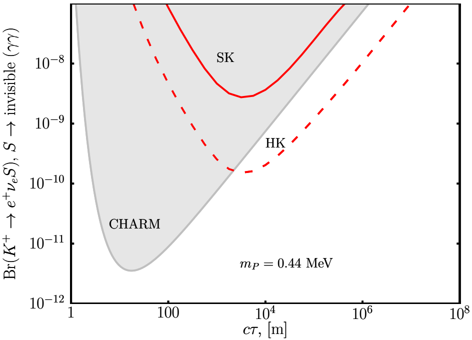
$K \to Pe\nu_e, P \to \gamma\gamma$

Pseudoscalar sgoldstino P
Production channels: $K^{\pm} \to Pe^{\pm}\nu_e$

$m_P = 0.28$ GeV



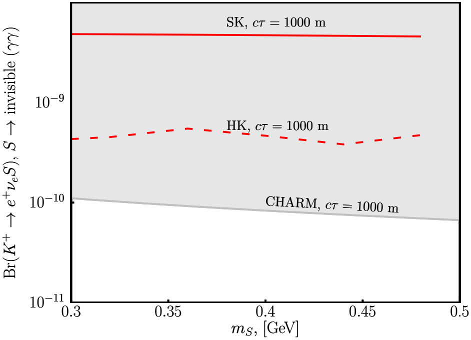
$m_P = 0.44$ GeV



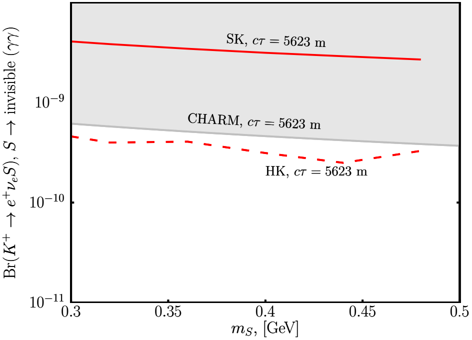
Pseudoscalar sgoldstino P

Production channels: $K^{\pm} \to Pe^{\pm}\nu_e, P \to \gamma\gamma$

$c\tau = 1000$ m



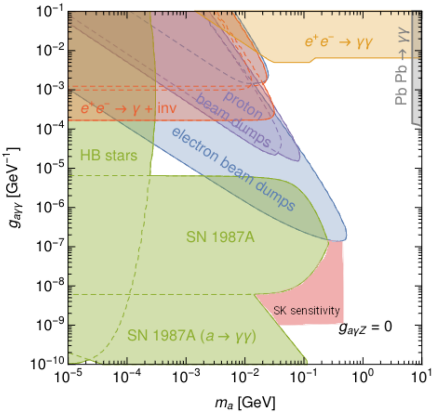
$c\tau = 5623$ m



Relevant parameter space of the model

- Sgoldstino ($S \to \gamma\gamma$) lifetime: 10^3 m$\lesssim c\tau \lesssim 10^6$ m
- $\frac{M_3}{F} \sim 10^{-7} - 10^{-9}$ GeV^{-1}

- Production S: $\frac{A}{F} \sim 4 \cdot 10^{-6}$ GeV^{-1}
- Production P: $\frac{M_3}{F} \sim 10^{-5}$ GeV^{-1}



Parameter space: $M_3 \gg A \gg M_{\gamma\gamma}$

Conclusions and future plans

- Atmospheric beam dump – an interesting avenue for searches of light long-lived particles
- Improved analysis: take into account signal from atmospheric neutrino
- Production of $S(P)$ in decays of heavier mesons such as $\eta, \eta', D, ...$

Thank you!

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